EFFECTS ACCOMPANYING GENERATION OF GIANT LASER PULSES

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The results of exact analysis of giant pulse generation are presented for the case when population and field variation along the resonator is significant. It is shown that a high gain of the active medium sharply alters the generation character and produces new phenomena causing oscillation of the output emission. One such phenomenon is of the same nature as that of population inversion oscillations previously investigated for the amplifier case. The second phenomenon consists of self-modulation of emission in the course of generation and causes a disruption of the single mode regime in the case of short high-intensity pulses.

1. DEFINITION OF THE PROBLEM AND METHOD OF SOLUTION

NONSTATIONARY processes of generation in solid-state lasers are usually analyzed without considering space relations; equations averaged over the length of the resonator are used instead, the equations being valid only when the transient generation processes are considerably longer than the photon flight time in the resonator. Exact equations describing the nonstationary laser emission are quite complicated and so far there are no solutions describing the giant pulse generation dynamics that take into account variation of population and fields along the resonator.

The present paper gives the exact solution of the problem for a traveling-wave oscillator that permits us to study the above processes and to reveal certain novel effects accompanying the generation of short pulses. Naturally these effects also take place in other types of Q-switched lasers.

We consider a Q-switched laser containing an excited ruby crystal with a length l placed in a ring resonator (Fig. 1). The analysis of the nonstationary generation process consists in the following. We denote the field in the resonator by $A(t, x)$. We consider field $A_0(t)$ in cross section $x = 0$ (front boundary of ruby) as external radiation entering the active medium. This field is amplified in passage through the crystal and can be computed as before for the amplifier[1-3] by a system of quasi-classical equations

$$\frac{\partial A}{\partial x}+\frac{1}{c}\frac{\partial A}{\partial t}+\frac{\beta}{2}A=\frac{2\pi}{\omega}\rho,\quad \frac{\partial\rho}{\partial t}+\left(i\varepsilon+\frac{\Gamma}{2}\right)\rho=\frac{|M|^2}{c\hbar}A\Delta,$$
$$\frac{\partial\Delta}{\partial t}=-\frac{2}{c\hbar}(A\rho^*+A^*\rho),\tag{1}$$

where A is the amplitude of the field vector potential, Δ is population inversion density, ρ is a quantity proportional to the non-diagonal component of the density matrix, c is the velocity of light in the medium, β is the nonresonance loss factor, $\epsilon = \omega_0 - \omega$ is the mismatch between the transition frequency and the external signal frequency (from now on it is assumed that $\epsilon = 0$), and M is the matrix transition element.

The amplified wave $A_l(t)$ continues to propagate in the hollow region of the resonator. A part of the energy of this wave passes through the semitransparent mirror

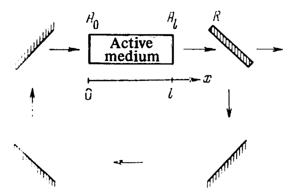

FIG. 1

(depending on the reflection coefficient R of the mirror) while the remainder is directed back to the forward ruby face by reflecting mirrors. If the photon flight time in the hollow region of the resonator is T the unique-solution condition requires that

$$A_0(t)=RA_l(t-T).\tag{2}$$

(Phase factors are omitted here on the assumption that the emission frequency coincides with one of the natural frequencies of the resonator). Condition (2) relates the amplitudes of the fields at the boundaries of the active medium and in a physical sense represents the continuity of field distribution along the resonator (taking radiation losses into account). Field $A_0(t)$ can be easily determined for the initial generation stage due to spontaneous noise when the emission intensity is low and population inversion variation in the ruby can be neglected. In this case the solution of (1) yields an exponential rise of emission amplitude along the active specimen (if the spectral width of the amplified signal is much narrower than the line width)[2]:

$$A_l(t)=A_0\left(t-\frac{l}{c}\right)\exp\left\{\frac{(\sigma\Delta_0-\beta)l}{2}\right\},\tag{3}$$

where Δ_0 is the initial value of population inversion and σ is the transverse cross section of the transition.

Relations (2) and (3) lead to a functional equation for the field amplitude at the forward boundary of the active medium

$$A_0(t)=RA_0\left(t-\frac{l}{c}-T\right)\exp\left\{\frac{(\sigma\Delta_0-\beta)l}{2}\right\}.\tag{4}$$

We readily find by direct substitution that the solution of this equation has the form

$$A_0(t)=C_0\exp\left\{\frac{(\sigma\Delta_0-\beta)l+2\ln R}{2(T+l/c)}t\right\},\tag{5}$$

where C_0 is a constant equal to the field amplitude at $x = 0$ at time $t = 0$.

Thus we found the solution of the problem at low field intensities. In fact, when field $A_0(t)$ is known at the cross section $x = 0$, the field at any point and the output emission field are uniquely determined. Since the quantity C_0 in (5) determined by the spontaneous noise level can be made as small as desired the above analytical solution which does not take the variation of population inversion in ruby into account is exact in the initial generation interval. If the pulse length at $x = 0$ is limited by $l/c + T$ the resonator is completely filled by radiation following this time interval. The generation then proceeds to develop automatically due to feedback.

The further development of generation can be analyzed by considering the successive passages of this pulse through the active medium.

The quantitative results given below were obtained with an electronic computer as an analytical solution quickly becomes complicated after several initial generation cycles. We note that the above solution (5) corresponds to the case when only a single longitudinal mode is excited in the resonator at the initial time. The method of solution remains the same for multimode generation except that an appropriate factor defining the amplitude and phase relations among the individual resonance modes at the initial time is introduced in the expression for the initial field at the section $x = 0$. For example this factor can be represented by a real periodic function for the case of in-phase (or opposed-phase) oscillations that are symmetric with respect to the center of the luminescence line.

2. SHAPE OF THE EMISSION PULSE

We first consider the case of an oscillator with a ruby specimen of the usual dimensions at room temperature. If the initial conditions are selected so as to excite a single longitudinal mode, then for the given parameters of the ruby the shape of the output pulse is determined by the resonator length $L = l + cT$. Figure 2 shows the computed time dependence of radiation intensity I (and power P) for the following parameters: $l = 12$ cm, $\Delta_0 = 10^{19}$ cm^{-3}, $\beta = 0.03$ cm^{-1}, and $r = |R|^2 = 0.9$.

As we see the output signal is a smooth pulse whose length rises linearly with increasing resonator length and whose peak power decreases. We note that the form of the dependence $\Delta t(L)$ and the numerical values of the pulse length are in a good agreement with the results obtained previously from equations averaged over the resonator length (the disagreement in the results lies within the limits of 10%). This follows directly from the fact that the characteristic time of the generation processes for the selected parameters is much longer than the photon flight time in the resonator. As is shown below, if this condition is not satisfied (i.e., the emission time of the active atoms is comparable to or shorter than the flight time) the results are significantly different.

As we noted above this method can also be used to compute the generation process for the case of several modes simultaneously excited at the initial time. As an example Fig. 3 shows the shape of a generation pulse for the case of three longitudinal modes

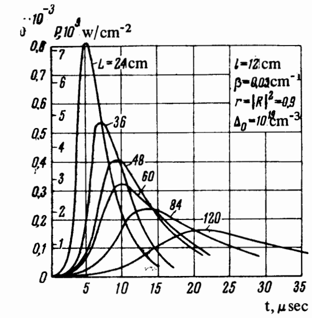

FIG. 2

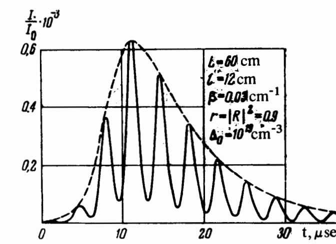

FIG. 3

($l = 12$ cm, $L = 60$ cm) excited in-phase at the initial time. The frequency of the central mode coincides with the center of the luminescence line. The other two neighboring modes are symmetric with respect to the first and have half the spectral amplitude. According to the computation the initial depth of modulation remains approximately the same in the generation process.

Thus the relations among the spectral intensities of various modes that are set up at the initial period of generation development remain without significant changes during the emission of the main power peak. This conclusion seems to be valid in all cases when the amplification of the active medium is not very large. We also note that the half-width pulse envelope remains in this case the same as in the excitation of a single mode (compare with Fig. 2).

3. THE HIGH-GAIN CASE. "SELF-MODULATION" EFFECT

Of considerable interest is the case of a high gain of the active specimen. For example, this can be realized by decreasing the temperature of the ruby crystal. Figure 4 shows a form of the emission pulse in an oscillator with an active ruby element at a liquid nitrogen temperature ($l = 2$ cm, $L = 4$ cm, $\Delta_0 = 19$ cm^{-3}, $\beta = 0.03$ cm^{-1}, $r = 0.5$, and $\Delta\nu = 0.3$ cm^{-1}). The initial signal was set up in the form (5) corresponding to the excitation of a single longitudinal mode.

Typical of this case is the fact that the emission from the active atoms occurs in a time shorter than the time of flight of the photons in the resonator. At that time the resonator gives rise to a short pulse whose length is limited only by the width of the transition line Γ. This pulse is repeatedly reflected between the mirrors and loses a portion of its energy in radiation. Therefore the output emission is modulated and represents a sequence of pulses separated by a time interval equal to the flight time around the resonator

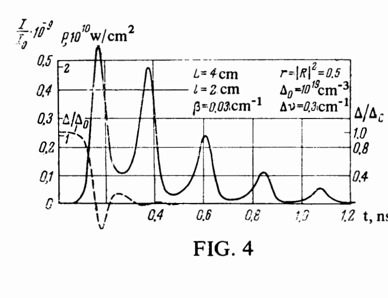

FIG. 4

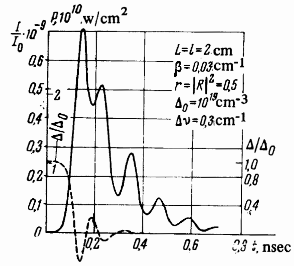

FIG. 5

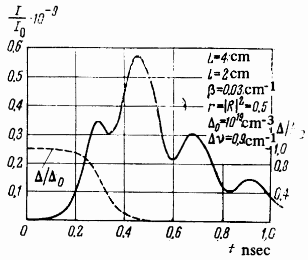

FIG. 6

circuit. This modulation is the result of a strong effect of the field on the active medium which, in turn, acts on the passing signal by distorting its shape. In the course of such a "self-modulation" the emission spectrum is significantly changed and corresponds to the generation of several (three or four in this case) longitudinal modes. Consequently the high gain of the active medium gives rise to a whole series of neighboring modes in the generation process instead of a single initial mode. In other words the single-mode regime is disrupted.

We note that it is usually considered in the analysis of ruby lasers that cooling of the active element and the corresponding narrowing of the luminescence line stimulate a reduction in the number of simultaneously generated modes because there are fewer modes within the limits of the linewidth. According to the above results however this is not always true of Q-switched lasers.

An interesting feature of the case under investigation is the oscillating character of the population inversion function Δ (Fig. 4) which can also take on negative values. This effect of Δ-oscillations investigated earlier for the case of the amplifier[1,3] is due to the fact that at high field intensities ($16\sigma I > \Gamma$) the characteristic time of interaction between the field and the particle system becomes comparable to the equilibrium stabilization time in the system, i.e., to the relaxation time $T_2 \approx 1/\Gamma$. Therefore the polarization of the medium has no time to "follow" the field variation and the field polarization process has an oscillatory nature. This phenomenon also leads to emission oscillations that are superimposed on the self-modulation effect examined above. Since the population inversion oscillations are quickly damped out they are observed only during the generation of the first two spikes in Fig. 4.

If the resonator length is reduced without changing the length of the active specimen the photon flight time in the resonator shortens causing a shortening of the total duration of generation. The distance between individual spikes is also shortened in this process. Figure 5 shows the shape of emission for a minimum length resonator (completely filled, $L = l = 2$ cm). We readily see that both effects under discussion also take place here and the emission pulses partly overlap instead of being separated as in Fig. 4.

Suitable selection of gain of the active sample can be made to suppress Δ-oscillation and to observe self-modulation in a pure form. This can be easily done because the Δ-oscillation effect has a threshold nature. For a ruby laser this case can be realized by a corresponding choice of crystal temperature. As an example Fig. 6 shows an emission pulse at a ruby temperature $T \approx 120^\circ$K (line width $\Delta\nu = 0.9$ cm^{-1}); the remaining parameters of the oscillator are the same as in Fig. 4. We see that in this case the oscillation of population inversion is practically suppressed and the output emission intensity oscillations are due only to the self-modulation effect. We note that this effect can apparently take place also at room temperature of the ruby if the length of the active sample is sufficient.

In reproducing this experiment one should use lasers with mode selection and also take measures to separate the above effects.

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